SURFACE SOLAR RADIATION FROM GEOSTATIONARY SATELLITES

Presented by

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SEAS Seminars: Sustainable Energy and Atmospheric Sciences
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NOAA Earth System Research Laboratory

Outline

- Current and future NESDIS/STAR satellite solar products and their evaluation
- NESDIS/STAR solar radiation algorithms

Application of Solar Radiation Data

- Climate
  - Cloud and aerosol forcing
- Surface energy budget models
  - Land surface and ocean assimilation models, models of coral reef health
  - Input of forcing term or evaluation
- Agriculture
  - crop modeling
- Hydrology
  - watershed and run-off analysis
- Fire risk
- Solar energy

SATELLITE SOLAR PRODUCTS AT NESDIS

Satellite Solar Products at NESDIS

- **Operational GOES-based products**
  - **GSIP-CONUS:**
    - GOES Surface and Insolation Product (GSIP) for the Contiguous United States (CONUS); (1996-2010)
  - **GSIP-fd:**
    - full disk version of GSIP at higher spatial resolution – Since May 2009
  - **GOES-R/ABI (under development):**
    - Downward Solar Radiation (DSR) at surface derived from the Advanced Baseline Imager (ABI) on the future GOES-R

Characteristics of GOES Surface Solar Radiation Products

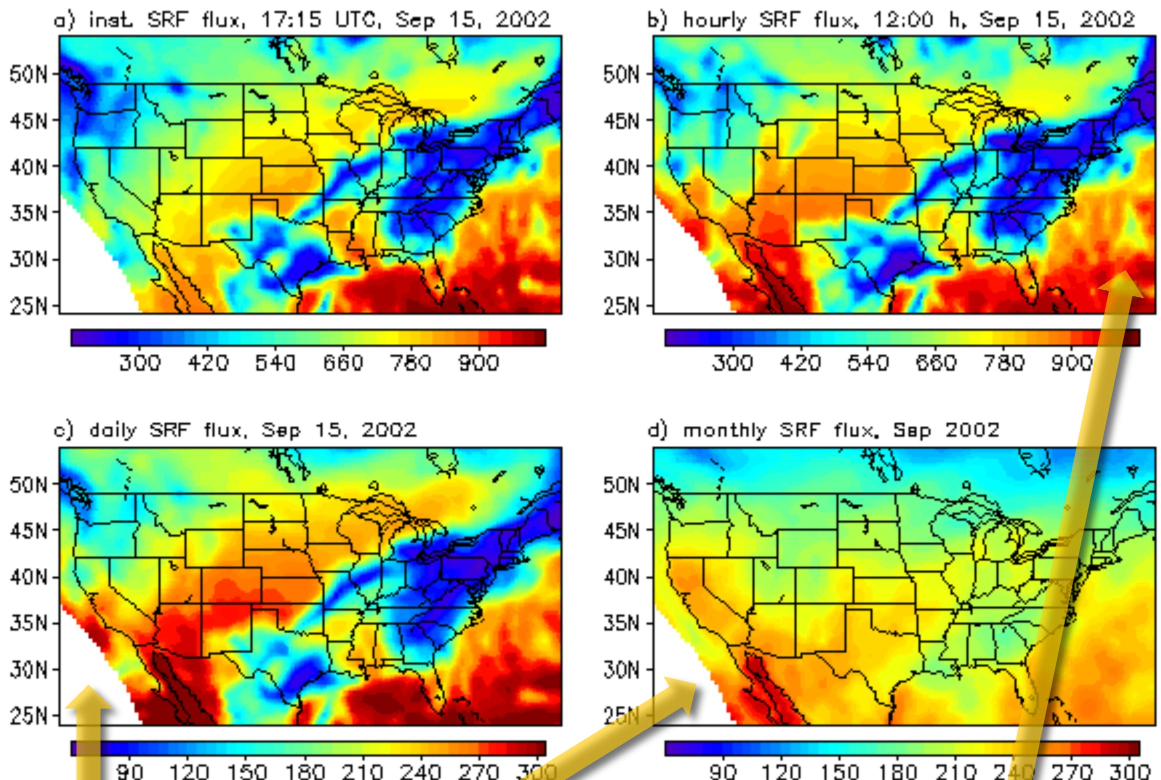
	Current		*Future*	
Product	**GSIP-CONUS**	**GSIP-fd**	**GSIP-fd-x**	**GOES-R/ABI**
Domain	CONUS	• Northern Hemisphere (NH) • Full Disk (FD)	• GOES • METEOSAT • MTSAT	• CONUS (C) • Full Disk (FD) • Mesoscale (M)
Spatial Resolution	~56 km (0.5x0.5 degrees)	~14 km (1/8x1/8 degrees)	~ 4 km	C: 25 km FD: 50 km M: 5 km
Temporal Resolution	instantaneous	instantaneous	instantaneous	instantaneous
Refresh rate	1 hour	1 hour (NH) 3 hours (FD)	1-3 hr	1 hour
Latency	50 minutes	50 minutes	50 minutes	54 minutes

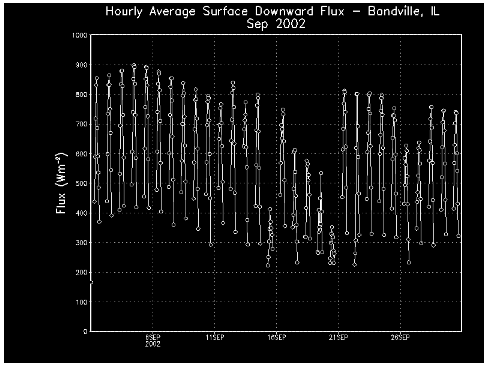
GOES Surface Solar Radiation Product Matrix

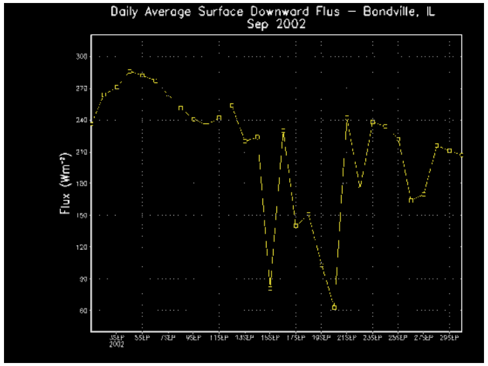
	Current		Future
Product	**GSIP-CONUS**	**GSIP-fd**	**GOES-R/ABI**
all-sky surface global downward SW flux	X	X	X
all-sky surface global upward SW flux	X	X	
all-sky surface diffuse downward SW flux	X		
all-sky surface global downward visible flux	X	X	
all-sky surface diffuse downward visible flux	X		
clear-sky surface global downward SW flux	X	X	
clear-sky surface global upward SW flux	X	X	
all-sky surface global absorbed (net) SW flux			X

global = direct + diffuse fluxes; SW=0.2-4.0 µm (solar); visible: 0.4-0.7 µm

GSIP-CONUS Product
Hourly/Daily/Monthly Averages





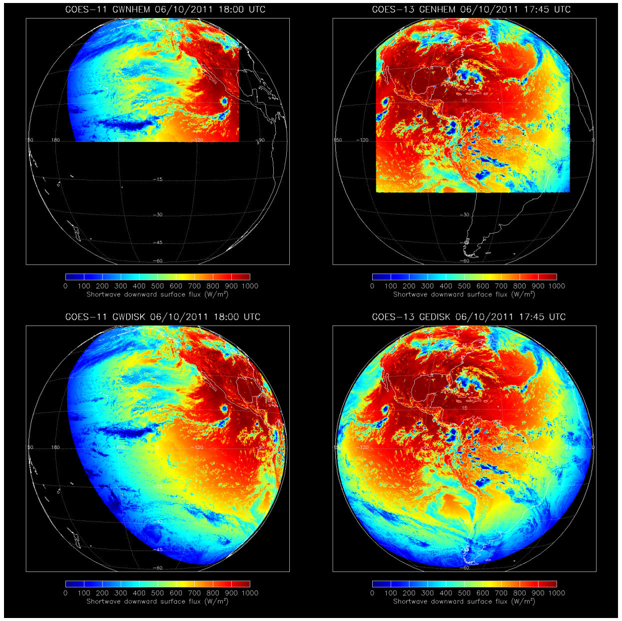


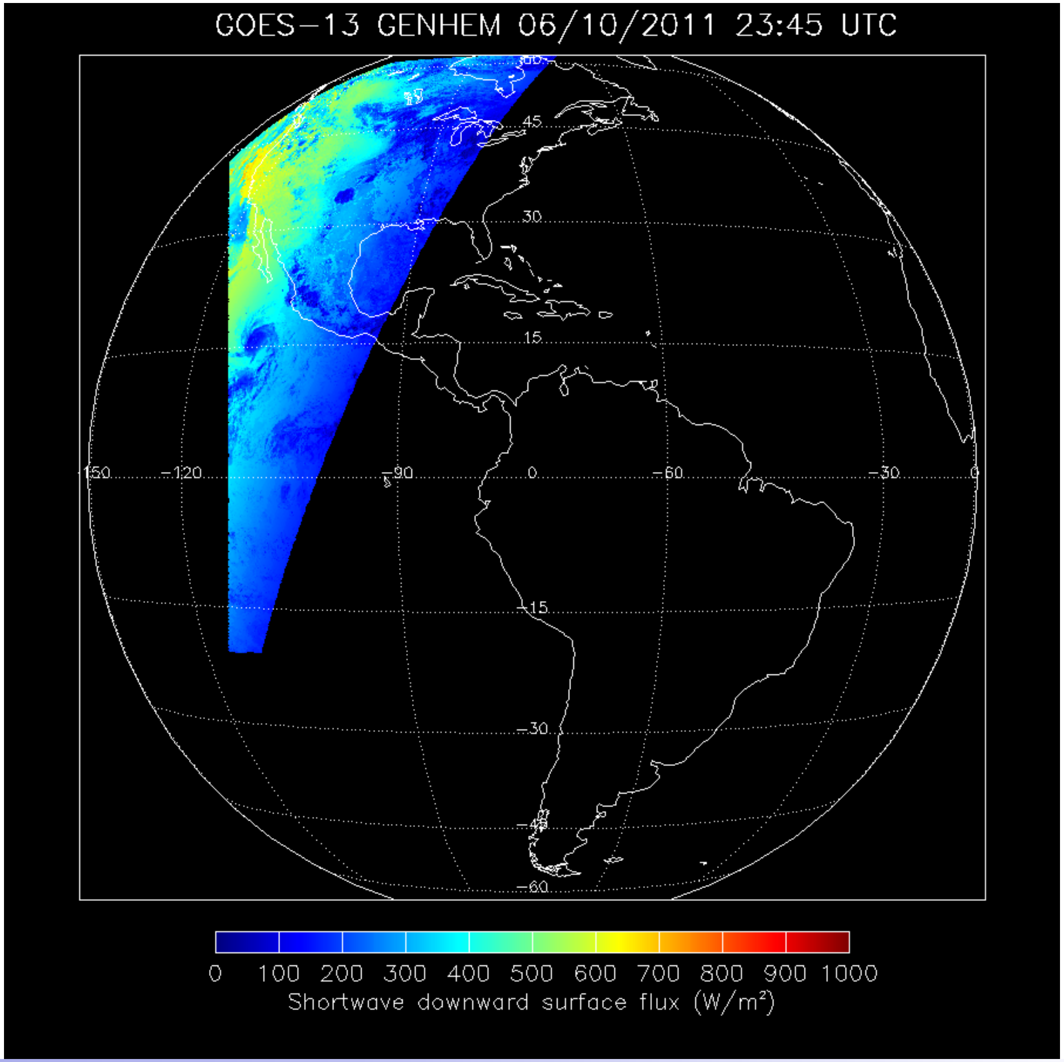
From the instantaneous GSIP-CONUS data hourly, daily and monthly averages are calculated.

Hourly and daily averages for Bondville, IL for September 2002

GSIP-fd Product Example:
GOES East Extended Northern Hemisphere

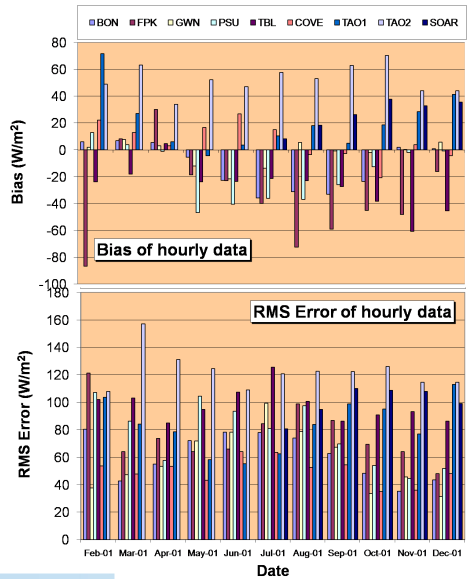
- GOES West
  - Extended Northern Hemisphere (hourly)
  - Full Disk (3 hourly)
- GOES East
  - Extended Northern Hemisphere (hourly)
  - Full Disk (3 hourly)

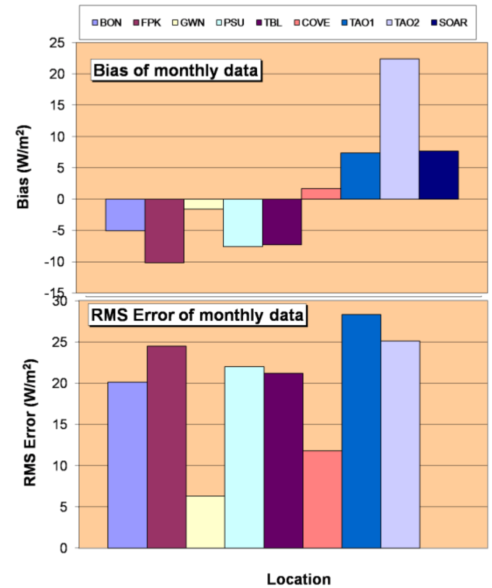


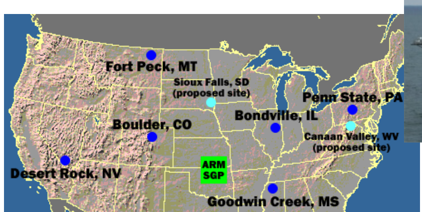


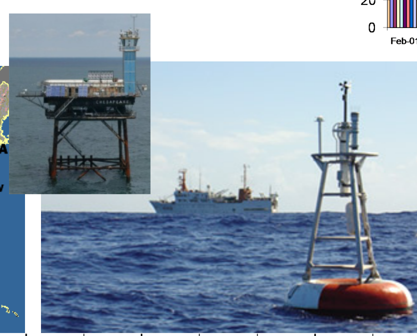
GSIP-fd Evaluation Results

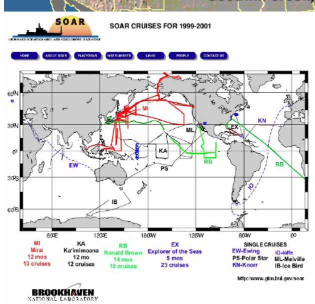
- Primary source of ground data is the NOAA Surface Radiation Budget Network (SURFRAD) over land, buoy and shipboard data over water.
- Evaluation is on different time scales (hourly, daily, monthly)
- Satellite-retrievals are averaged in space (50 km)
- Ground data are averaged in time (one hour)

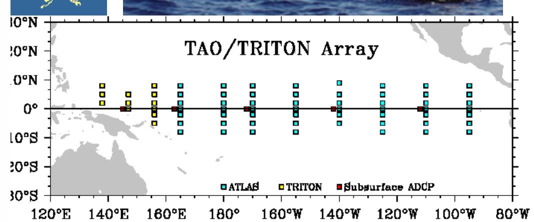


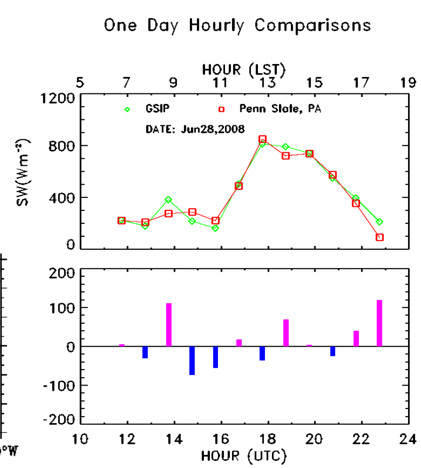


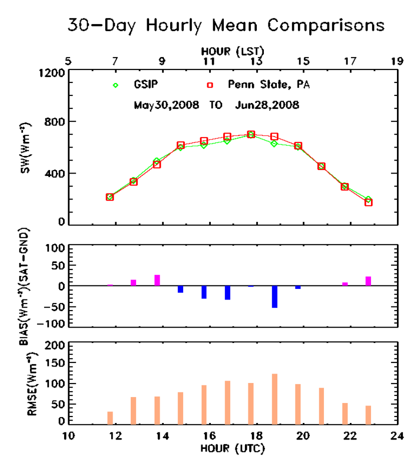








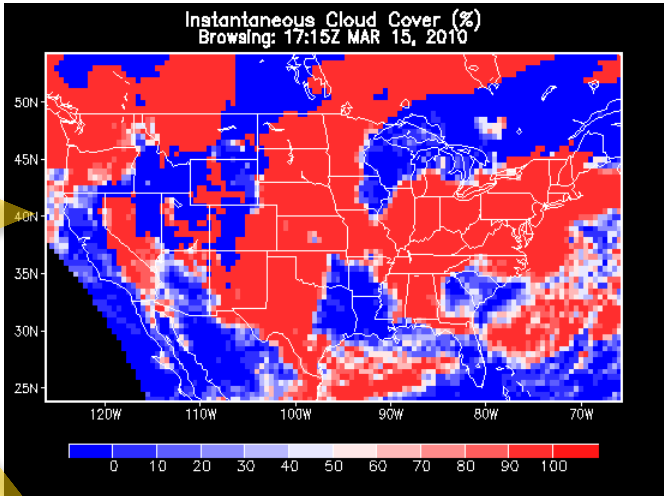




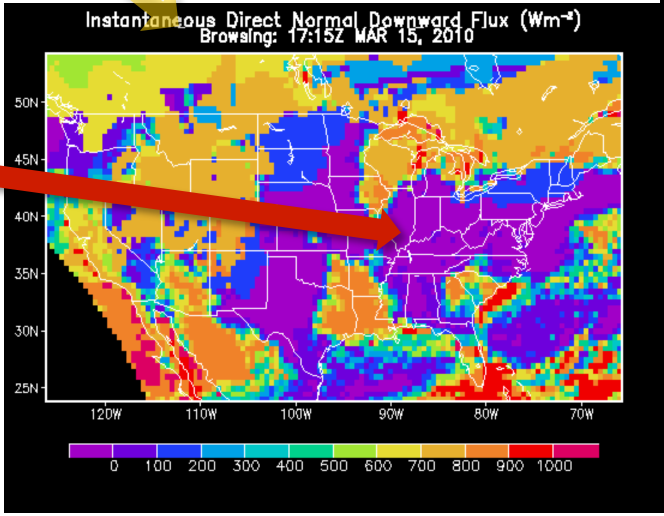
DATA FOR SOLAR ENERGY APPLICATIONS

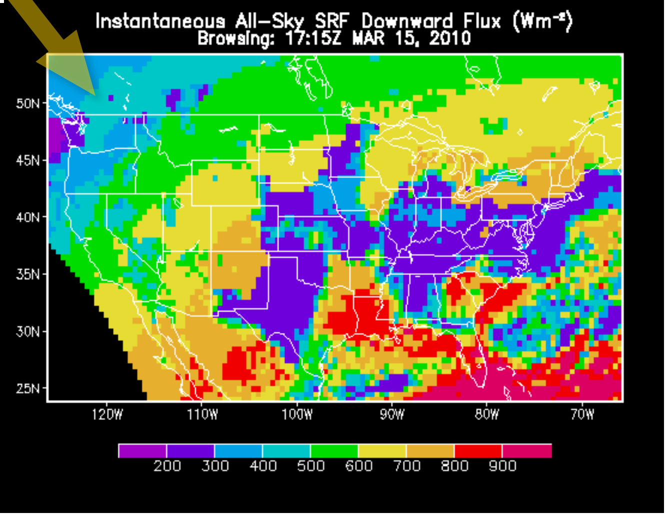
GSIP-CONUS Product

- Examples of the GSIP-CONUS product for March 15, 2010 at 17:15 UTC
  - cloud cover
  - global (direct+diffuse) surface insolation
  - direct normal flux at surface
    - calculated as (global-diffuse)/cos(solar zenith angle)



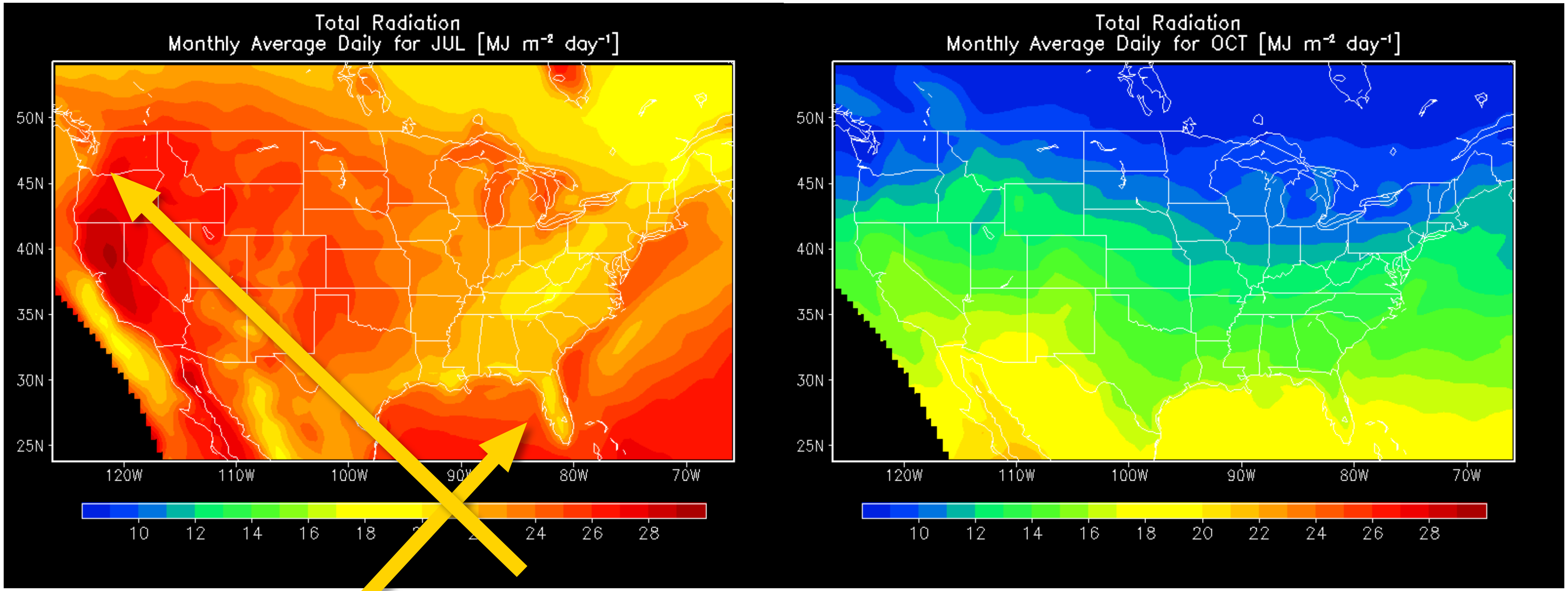
- No direct radiation at surface due to optically thick clouds.
- CSPs will not operate – utility company must use other (convectional) means to generate electricity.





GSIP-CONUS SE Examples: Monthly Average Daily Total Radiation

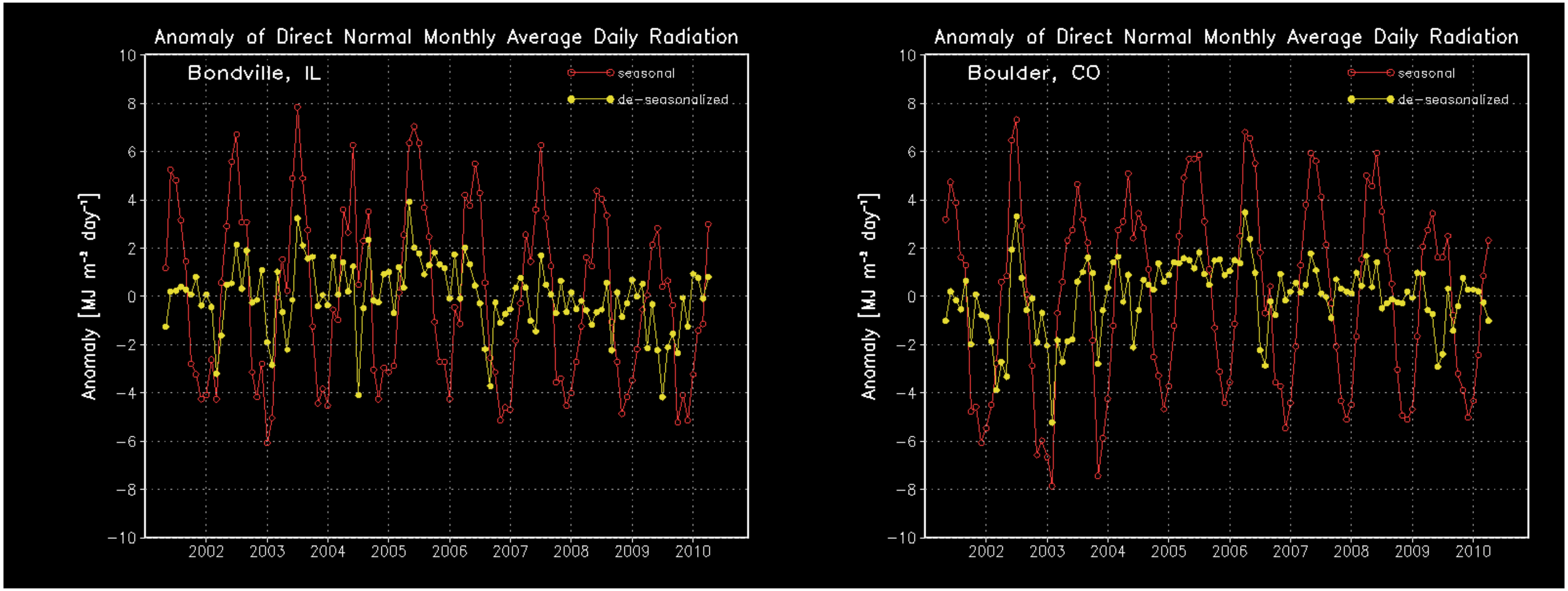
- 10-year monthly averages of total solar radiation for July and October
- ~8 MJ m^{-2} day^{-1} difference between western and eastern US in July in available solar energy
- ~8 MJ m^{-2} day^{-1} difference between July and October



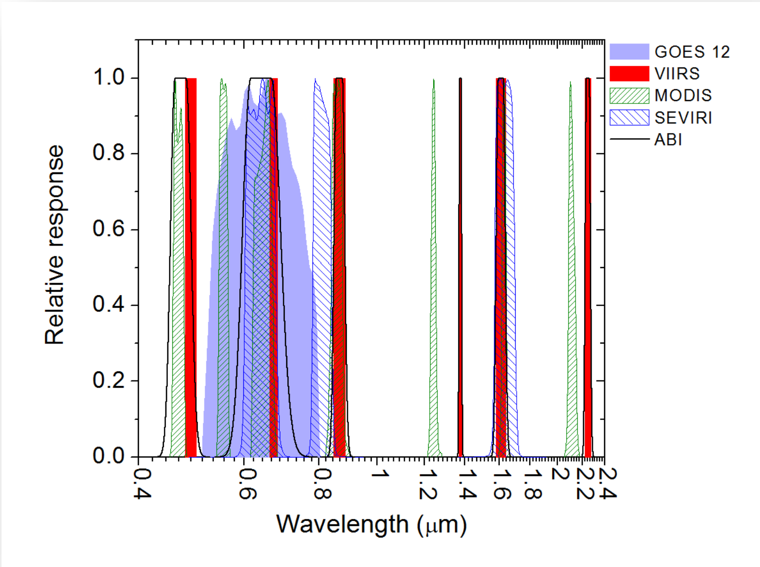
In July southern Florida receives less solar radiation than northern Washington state; in October it gets about the same as "sunny" California

GSIP-CONUS SE Examples: Anomaly of Monthly Average Daily Direct-Normal Radiation

- Time series of anomalies of monthly average Direct-Normal Radiation for Bondville, IL and Boulder, CO
    - red: 10-year average subtracted,
    - yellow: 10-year monthly average subtracted



Radiation Budget from GOES-R & ABI



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- **Advanced Baseline Imager (ABI)**
  - 16-band, two-axis scanning passive radiometer with star sensing
  - measures emitted and solar reflected radiance simultaneously in all spectral bands
  - **first imager with onboard calibration of solar reflective channels on a US geostationary platform!**

ABI channels

Channel ID	*Wavelength Microns*	*Hor. Res.*	*Upper and lower 50% response points (in microns)*	*Noise @ Ref.*	*Max. Level*
1	0.47	1km	0.45±0.01 - 0.49±0.01	300/1	100 %
2	0.64	0.5km	0.59±0.01 - 0.69±0.01	300/1	100 %
3	0.865	1km	0.8455±0.01 - 0.8845±0.01	300/1	100 %
4	1.378	2km	1.3705±0.005 -1.3855±0.005	300/1	100 %
5	1.61	1km	1.58±0.01 - 1.64±0.01	300/1	100 %
6	2.25	2km	2.225±0.01 - 2.275±0.01	300/1	100 %
7	3.90	2km	3.80±0.05 - 4.00±0.05	0.1 K	400 K
8	6.185	2km	5.77±0.03 - 6.6±0.03	0.1 K	300 K
9	6.95	2km	6.75±0.03 - 7.15±0.03	0.1 K	300 K
10	7.34	2km	7.24±0.02 - 7.44±0.02	0.1 K	320 K
11	8.5	2km	8.3±0.03 - 8.7±0.03	0.1 K	330 K
12	9.61	2km	9.42±0.02 - 9.8±0.03	0.1 K	300 K
13	10.35	2km	10.1±0.1 - 10.6±0.1	0.1 K	330 K
14	11.2	2km	10.8±0.1 - 11.6±0.1	0.1 K	330 K
15	12.3	2km	11.8±0.1 - 12.8±0.1	0.1 K	330 K
16	13.3	2km	13.0±0.06 - 13.6±0.06	0.3 K	305 K

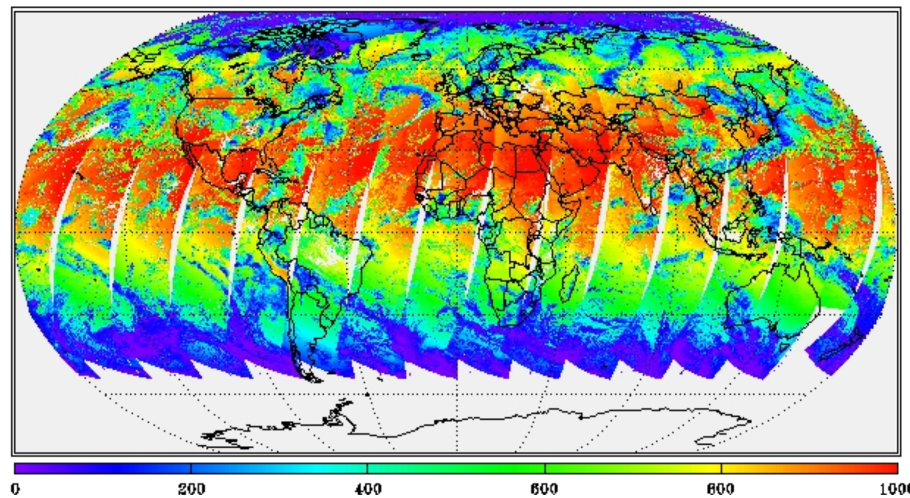
ABI SE Example:
Total, Direct & Diffuse Radiation

Date: June 11, 2009

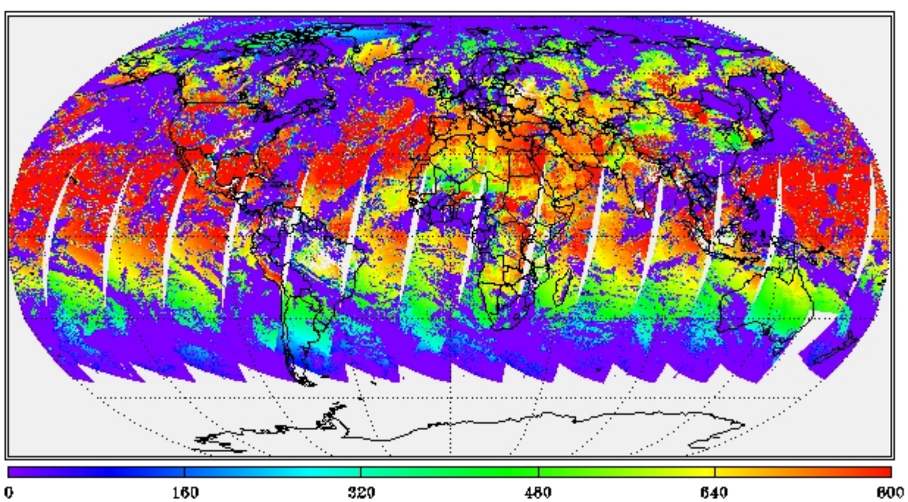
Input satellite data: MODIS Terra

Spatial resolution: 5-km

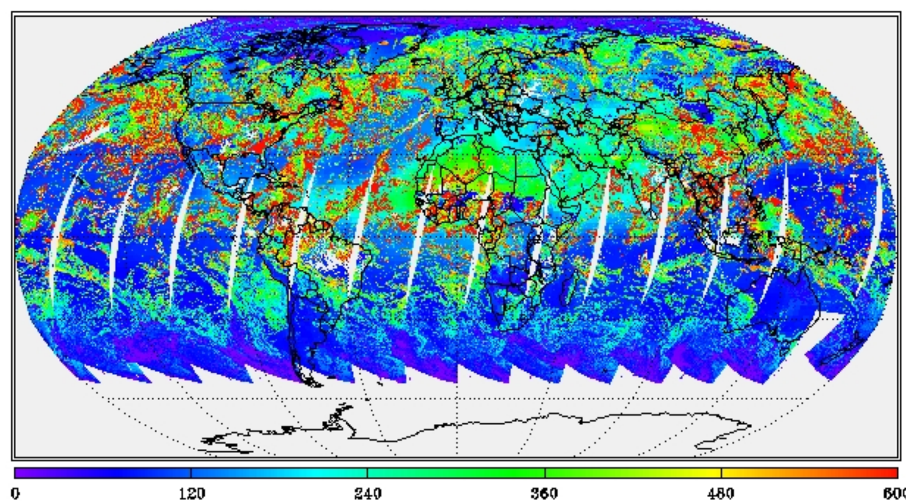
Surface Downward Shortwave Flux (Wm^{-2})



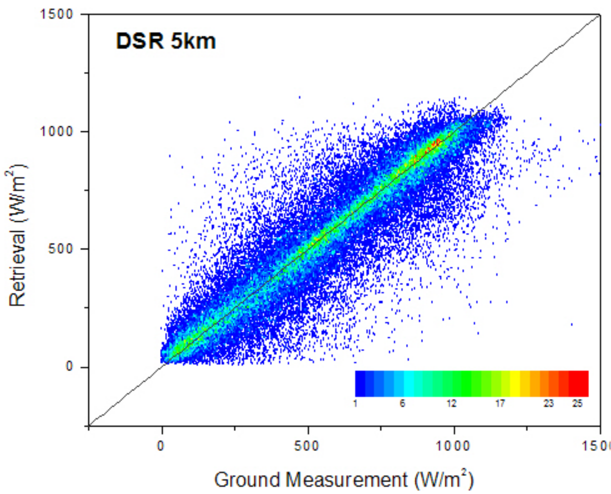
Surface Downward Direct Shortwave Flux (Wm^{-2})

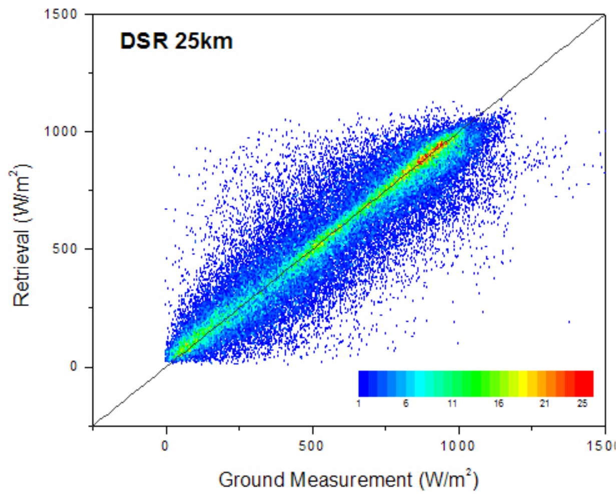


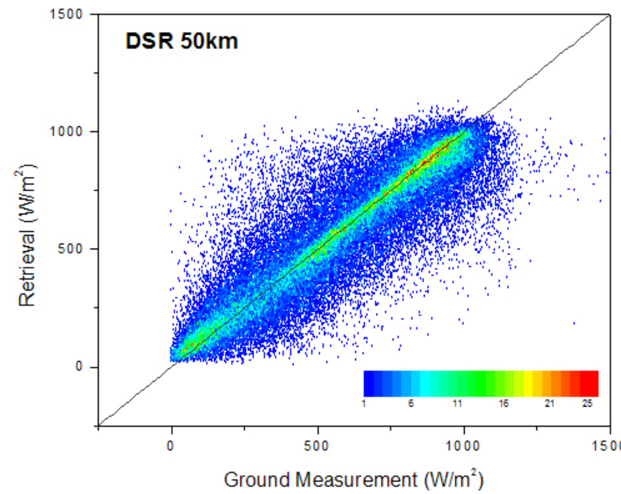
Surface Downward Diffuse Shortwave Flux (Wm^{-2})

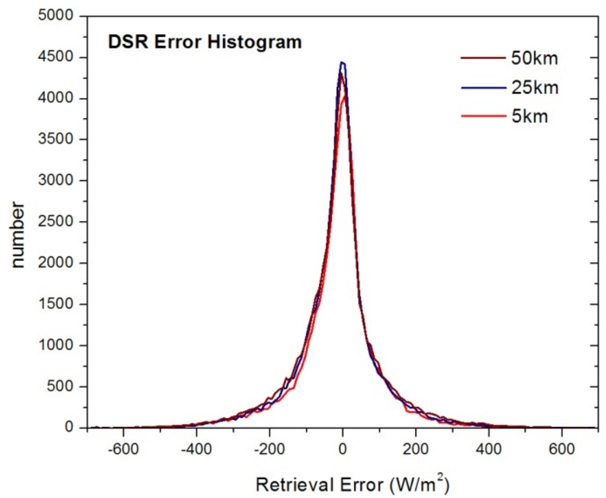


Evaluation of ABI Downward Solar Radiation, DSR









Based on 10 years of data over 13 sites:

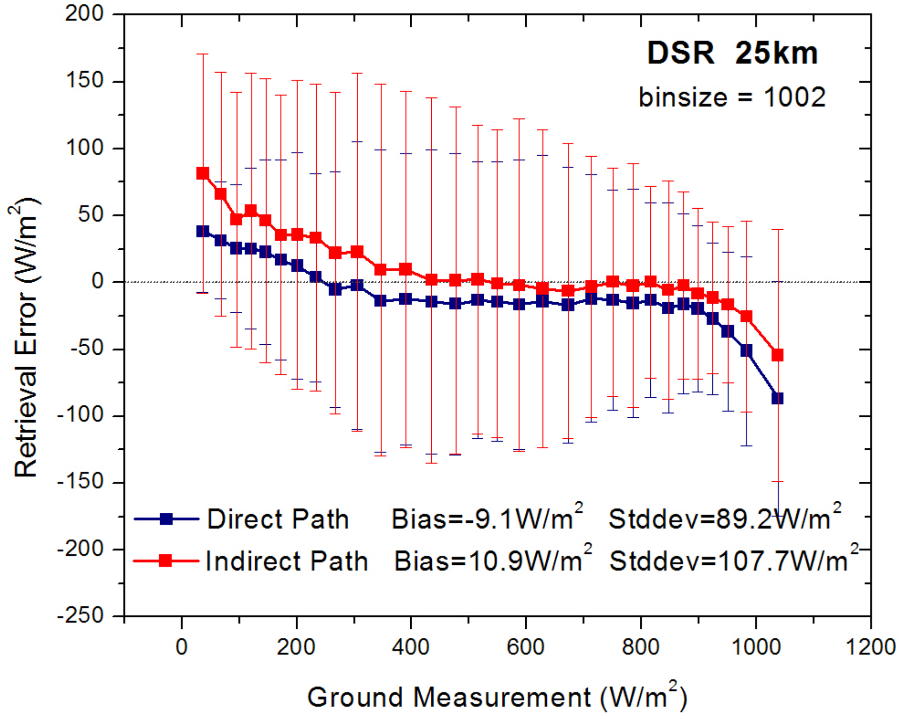
Similar performance of retrievals at the three spatial resolutions (5, 25, and 50 km):

overall accuracy: ~ -10 W/m^2

precision: ~ 100 W/m^2

Evaluation of ABI Downward Solar Radiation, DSR

- accuracy/precision vs. ground observations
  - symbols: bias
  - whiskers: 1-σ standard deviation
  - accuracy is a function of “true” flux
    - over (under) estimation at low (high) value
  - ABI algorithm does not perform equally well for all ranges of “true” fluxes



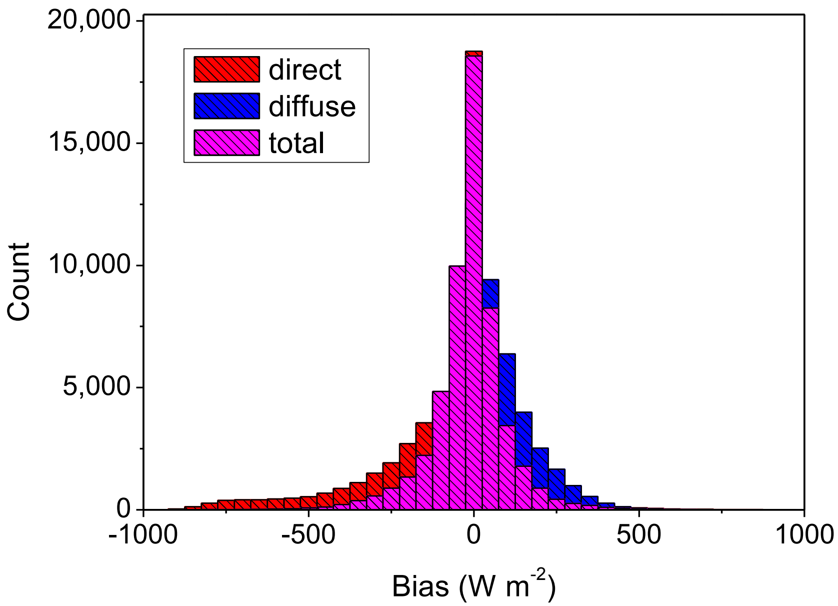
ABI DSR Validation Summary

DSR	50km			25km			5km		
	Number of retrievals	Accuracy (W/m^2)	Precision (W/m^2)	Number of retrievals	Accuracy (W/m^2)	Precision (W/m^2)	Number of retrievals	Accuracy (W/m^2)	Precision (W/m^2)
Low (<200W/m^2)	8114	42 (110)	92 (100)	8059	32 (110)	84 (100)	7791	24 (110)	76 (100)
Medium [200, 500]	15529	44 (65)	98 (130)	15257	43 (65)	95 (130)	14692	46 (65)	97 (130)
High (>500W/m^2)	34447	25 (85)	89 (100)	34128	23 (85)	84 (100)	30840	16 (85)	82 (100)

Evaluation of ABI SE Products MODIS Inputs

	Number	Accuracy	Precision	RMSE
Total	54163	-14 (-3%)	113 (20%)	114 (20%)
Direct	54163	-46 (-13%)	159 (43%)	165 (45%)
Diffuse	54163	+33 (+16%)	121 (59%)	126 (62%)

Accuracy, precision and RMSE are in W/ m^2



- Errors of instantaneous direct and diffuse components are larger than error of total flux
- ABI algorithm under/over-estimates the direct/ diffuse component
- Relatively small error of total flux is result of cancellation of errors in direct and diffuse components

METHODS AND ALGORITHMS

Methods

- *Empirical*:

  Use parameterized relationships between simultaneously observed TOA fluxes and surface fluxes. (Fast but not general)

- *Physical*:

  Use observed/retrieved atmosphere and surface parameters. (General)

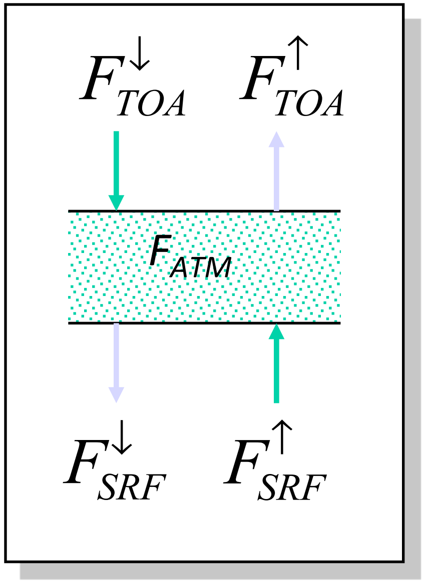
  – "Transmittance" approach
  – "Energy-balance" approach
  – distinction is not always obvious: some algorithms determine transmittance while conserving energy

"Transmittance" approach

- *Assumption:* T can be
  - estimated from the satellite-observed TOA reflectance R_{TOA},
    - Examples: Dedieu et al., 1987; Marsouin et al., 1989; Darnell et al., 1992.
  - calculated from RT knowing the atmosphere and surface.
    - Examples: CERES/SARB, GOES-R ABI direct path algorithms

$$F_{SRF}^{\downarrow} = T\ F_{TOA}^{\downarrow}$$

"Energy balance" approach



$$F^{\downarrow}_{TOA} + F^{\uparrow}_{SRF} = F^{\uparrow}_{TOA} + F^{\downarrow}_{SRF} + F_{ATM}$$

$$F^{\downarrow}_{SRF}(1 - A_{SRF}) = F^{\downarrow}_{TOA} - F^{\uparrow}_{TOA} - F_{ATM}$$

Assumption: A_{SRF} and F_{ATM} can be determined from satellite-observed TOA reflected radiation.

Examples: Gautier et al., 1980; Stuhlmann et al., 1990; Pinker and Laszlo, 1992; Zhang et al., 1995, Laszlo et al., 2008.

Principle of deriving F_{ATM} and T from R_{TOA}

- There is a strong correlation between TOA reflectance R_{TOA} and atmospheric transmittance T.

$$\left.\begin{aligned} R &= f\left(\tau_m,\tau_a,\tau_c,\tau_{H_2O},\tau_{O_3},A_s,\vartheta_0,\varphi_0,\vartheta_s,\varphi_s\right) \\ T &= g\left(\tau_m,\tau_a,\tau_c,\tau_{H_2O},\tau_{O_3},A_s,\vartheta_0,\varphi_0,\vartheta_s,\varphi_s\right) \end{aligned}\right\} \Rightarrow \quad T = h(R)$$

  – Function h depends on the same quantities as R and T depend on. The form of h can be determined from RT or empirically.

Error sources

- Approximation of physical processes.
- Uncertainties in ancillary atmospheric data.
- Calibration.

  Vicarious calibrations have an accuracy of about 5-10% (Schmetz, 1989). A 10% error leads to errors of 2-10% in surface flux for clear sky (Gautier and Frouin, 1988).
- Determination of cloud fraction.
- Under-sampling of radiation field in time.
- [Space and time scales represented by satellite and ground measurements are *different* – not strictly an error in retrieval, but does make evaluation more difficult.]

Effect of cloud "contamination"

- In "transmittance" approach:
  - $T_{cld} \sim (R_{max}-R_{TOA}) / (R_{max}-R_{min})$
  - $R'_{min} > R_{min} \Rightarrow T'_{cld} > T_{cld} \Rightarrow F^{\downarrow'}_{SRF} > F^{\downarrow}_{SRF}$

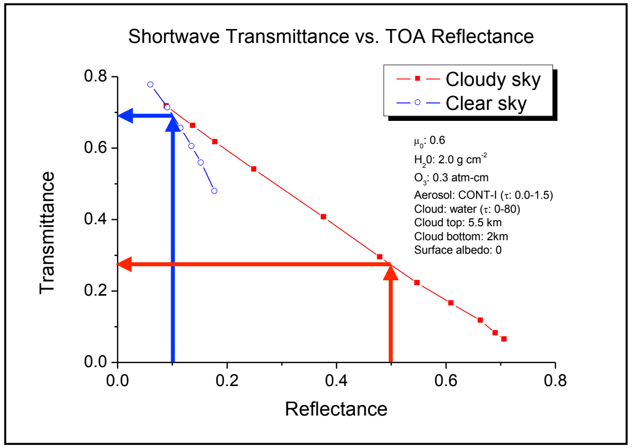
- In "energy balance" approach:
  - $R'_{clr} > R_{clr} \Rightarrow t'_{clr} > t_{clr} \Rightarrow F^{\downarrow'}_{SRF} < F^{\downarrow}_{SRF}$

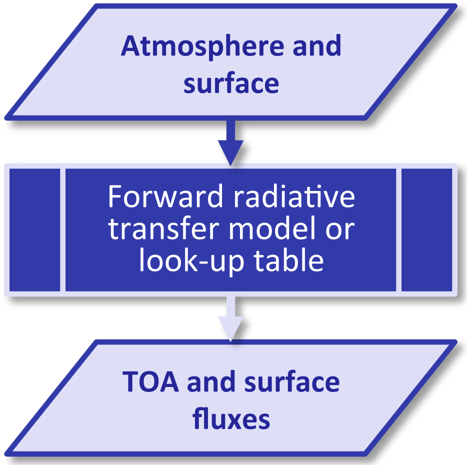
Baseline Cloud Mask in GSIP-fd (Andrew K. Heidinger (STAR))

- The Baseline cloud mask is the Clouds from AVHRR Extended (CLAVR-x) cloud mask applied to GOES-R
  - CLAVR-x cloud mask documentation from OSDPD and http://cimss.ssec.wisc.edu/clavr
- Contains several tests to determine cloud mask.
  - Thermal Uniformity Test
  - Reflectance Uniformity Test
  - Reflectance Gross Contrast Test
  - Thermal Gross Contrast Test
  - RTCT - Relative Thermal Contrast Test
  - RVCT - Relative Visible Contrast Test
  - Emissivity at Tropopause Test

Theoretical Basis of ABI Insolation Retrieval

- Two approaches are used for estimating transmittance:
  - derived from top of atmosphere (TOA) reflectance
  - calculated directly from data characterizing the atmosphere and the surface
- Both approaches are based on radiative transfer (Fu-Liou four-stream) modeling that accounts for absorption and scattering by gases, aerosols and clouds. Results are in LUT for speed.





Calculation of Reflectance and Transmittance (1)

The total transmittance (T^0) and reflectance (R^0) of the atmosphere is determined by the optical depth (τ) of molecules (*m*), aerosol (*a*), cloud (*c*), water vapor (H_2O), and ozone (O_3), the aerosol single-scatter albedo (ω_s), solar zenith (ϑ_0) and azimuth (φ_0) angles, and satellite zenith (ϑ_S) and azimuth (φ_S) angles

$$
\begin{aligned}
R^0 &= f\left(\tau_m, \tau_a, \tau_c, \tau_{H_2O}, \tau_{O_3}, \tau_{other}, \omega_s, \vartheta_0, \varphi_0, \vartheta_s, \varphi_s\right) \\
T^0 &= g\left(\underbrace{\tau_m, \tau_a, \tau_c, \tau_{H_2O}, \tau_{O_3}, \tau_{other}}_{\text{atmosphere}}, \omega_s, \underbrace{\vartheta_0, \varphi_0, \vartheta_s, \varphi_s}_{\text{geometry}}\right)
\end{aligned}
\qquad (1)
$$

- Atmospheric reflectances and transmittances are pre-calculated using the NASA/LaRC modified Fu-Liou RTM (*Fu*., 1996) and stored in LUT for speed.

Calculation of Reflectance and Transmittance (2)

Surface reflection is added to yield total TOA reflectance (albedo) (*R*) and surface downward transmission (*T*) (Chandrasekhar, 1956).

(2a) $$R(\vartheta_0) = R^0(\vartheta_0) + r\tilde{T}$$

(2b) $$T(\vartheta_0) = T^0(\vartheta_0) + r\tilde{R}$$

surface contribution transmitted to TOA

surface contribution back-reflected by atmosphere

atmospheric reflectance and transmittance (no surface)

accounts for multiple reflection between atmosphere and surface

where $$r = \left[1 - a_{dif}(\vartheta_0)\tilde{R}\right]^{-1}\left[a_{dir}(\vartheta_0)T^0_{dir}(\vartheta_0) + a_{dif}(\vartheta_0)T^0_{dif}(\vartheta_0)\right].$$

- **Subscripts "dir" and "dif" refer to the direct and diffuse components of *R* and *T* and those of the surface albedo (*a*). $\tilde{R}$ and $\tilde{T}$ are the spherical reflectance and transmittance.**
- $R^0, T^0_{dir}, T^0_{dif}, \tilde{R}$ **and $\tilde{T}$ are obtained from LUT**

Calculation of TOA & Surface Radiation

- Reflected SW radiation: TOA (RSR)

$$RSR = R(\vartheta_0) S_0 \cos\vartheta_0 \frac{d_0^2}{d^2} \qquad \textbf{(3)}$$

Solar irradiance at TOA

- Downward SW radiation: Surface (DSR)

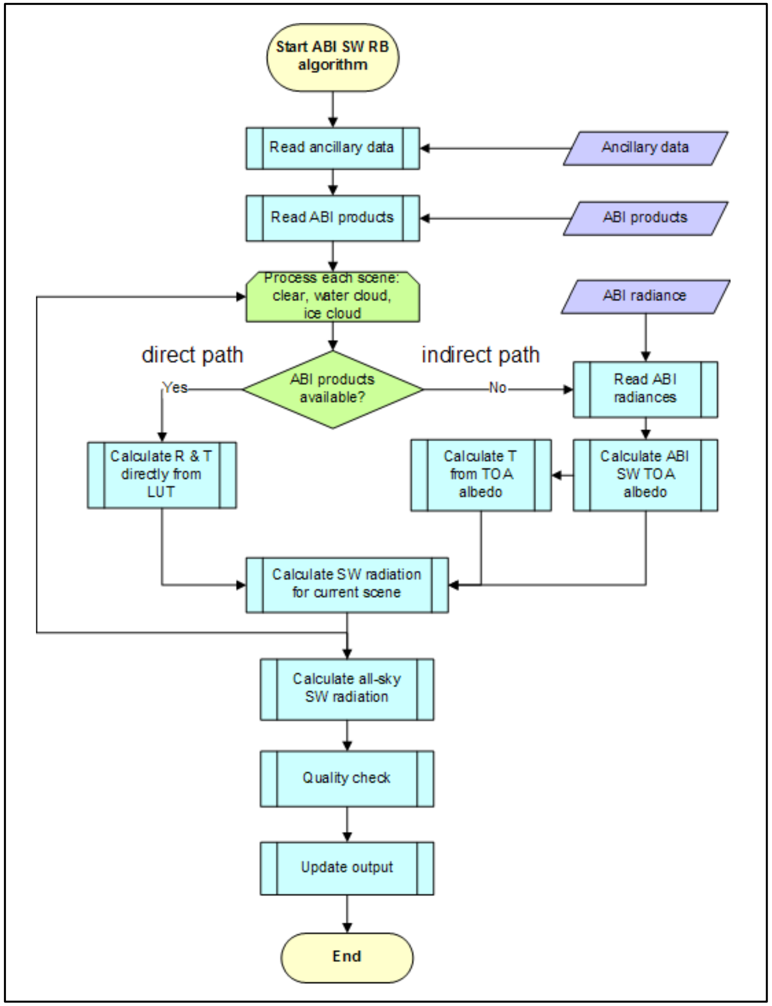
$$DSR = T(\vartheta_0) S_0 \cos\vartheta_0 \frac{d_0^2}{d^2} \qquad \textbf{(4)}$$

d **and** $\boldsymbol{d_0}$ **are the actual and mean Sun-Earth distances, respectively.**

$\boldsymbol{S_0}$ **is the solar "constant".** $\boldsymbol{\vartheta_0}$ **is the solar zenith angle.**

ABI Solar Radiation Algorithm

- Two independent algorithms performing physically-based retrieval of reflectances and transmittances by using LUT representation of RTM
- **Direct Path Algorithm (DPA)**
  - used when atmospheric & surface inputs are available
  - uses GOES-R products (AOD, COD, surface albedo, etc.) as inputs , and thus more consistent with other ABI products
  - RT version proven with CERES
  - straightforward computation with low latency
  - *Disadvantage*: some inputs (e.g., AOD over bright surface) are not available everywhere
- **Indirect Path Algorithm (IPA)**
  - used when NOT all inputs needed in DPA are available
  - uses ABI reflectances for estimating TOA albedo
  - estimates DSR by comparing satellite-estimated broadband TOA albedo to calculated ones
  - proven in GEWEX/SRB and has been tested in an operational environment (NOAA/GSIP)
  - *Disadvantage*: broadband TOA albedo is not directly measured; it requires spectral and angular corrections, which introduce (additional) uncertainties

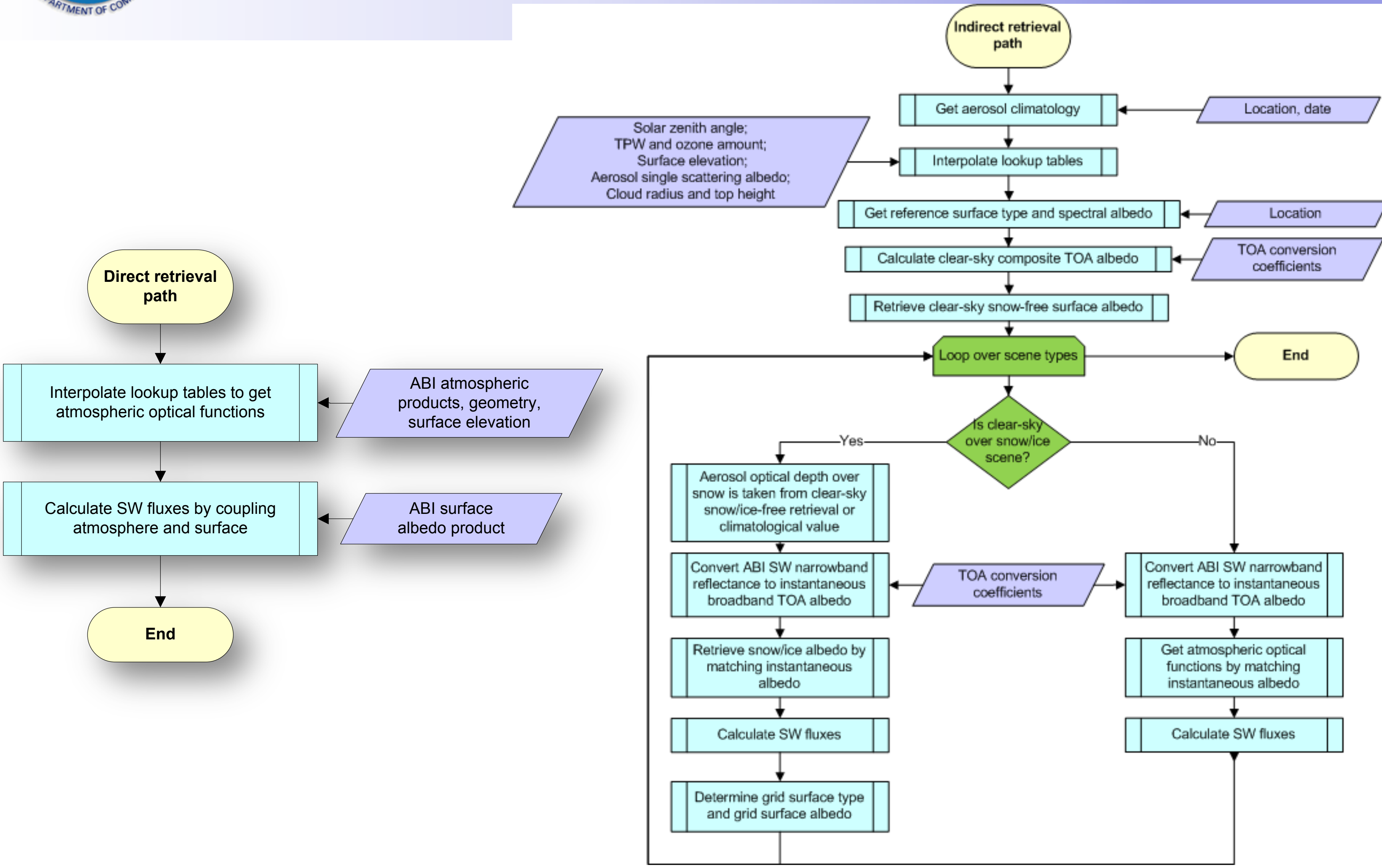


ABI Indirect Path

(GSIP-CONUS, GSIP-fd)

- Task: estimate *T* given $\square_{H2O}$, $\square_{O3}$, $\square_{m}$
  - must estimate $\square_{a}$, $\square_{c}$ and A_s from satellite-observed reflectance:
    - separate reflectances into clear R_{clr} and cloudy R_{cld} groups, and
    - estimate $\square_{a}$ and A_s from R_{clr}
      - temporally, $\square_{a}$ is more variable than A_s
      - assume A_s is constant over several days (~28 days), and $\square_{a}$ varies around a known value $\square_{clm}$
      - create a composite clear reflectance R_{ccr} from R_{clr} over this period, and
      - retrieve A_s from R_{ccr} using $\square_{clm}$
      - retrieve $\square_{a}$ from individual R_{clr}
    - estimate $\square_{c}$ from R_{cld} and A_s assuming fixed $\square_{a}$

Flowchart of ABI Algorithm



TOA Broadband Albedo

1. Narrowband reflectances in 3 ABI channels (0.47, 0.64, 0.86 μm) $R_{n,i}$ are converted into broadband BRDF R_b

$$R_b = c_0 + \sum_{i=1}^{3} c_i R_{n,i}$$

   Coefficients c_i are obtained for discrete solar zenith angle bins from regression of simulated (MODTRAN, *Berk et al.*, 1985) narrowband and broadband BRDF.

2. CERES on TRMM (*Loeb et al.*, 2003; *Kato and Loeb*, 2005) ADM is applied to R_b to get broadband TOA albedo.

The "GOES Solar Radiation Products in Support of Renewable Energy" Project

- **Objective:** Modify/improve and test the geostationary solar radiation budget algorithms such that they meet the requirements of solar energy (SE) industry.
- **Tasks:**
  - – use EOS aerosol and surface reflectance data;
  - – add tailored products (e.g., averages);
  - – add direct normal and diffuse radiation as products (GOES-R);
  - – increase spatial resolution (4 km for GSIP, 2 km for GOES-R);
  - – add solar radiation from METEOSAT and MTSAT (GSIP-fd);
- **Team:** NOAA (STAR: I. Laszlo, H. Liu, M. Goldberg, F. Weng; A. Heidinger (UW); OAR/ESRL: E. Dutton) + US Department of Energy (DOE)/National Renewable Energy Laboratory (NREL)

Plans

Other planned activities:

- develop data access mechanisms that better suit SE needs
- provide algorithm/results for comparison with other algorithms
- generate climatology of SE parameters from current GOES
- use broadband measurements of TOA radiation (e.g. ERBE, CERES) to constrain SW surface radiation estimates from GOES
- use satellite insolation product for evaluating models that assimilate satellite information on clouds and aerosol to forecast SE

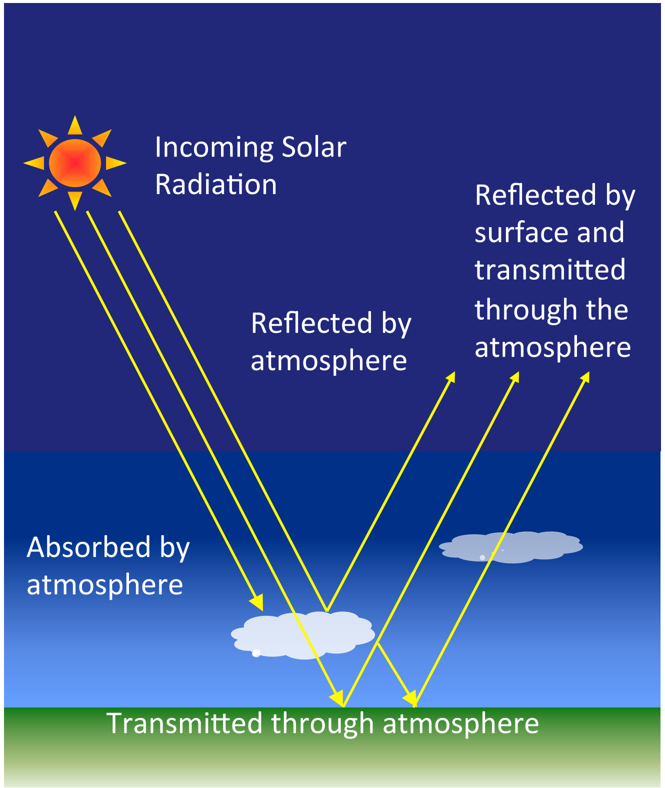
Summary

- Solar radiation data over CONUS for 1996-2010 are available
- GSIP-fd product provides solar radiation data near real time for every daytime hour
- GOES-R ABI product will be derived from an improved instrument and with a state-of-the-art algorithm
- Tailored, SE specific data are coming

BACKUP

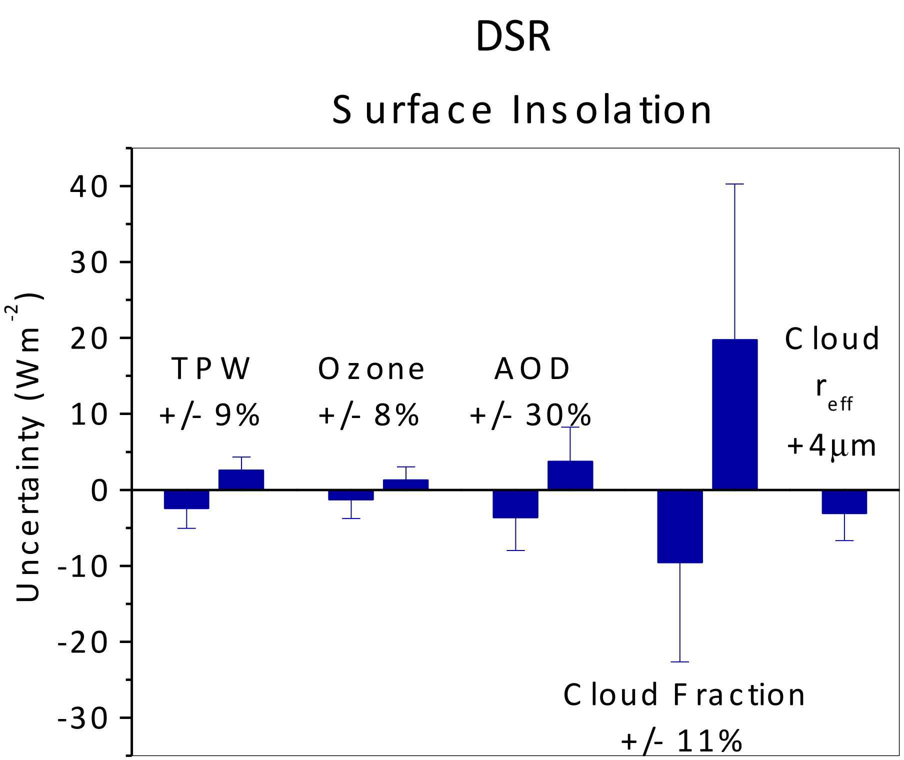
Physical Basis

- Incoming solar radiation undergoes reflection, scattering and absorption by molecules, aerosol, cloud and surface.
- Estimation of SW radiation needs information about atmospheric gases, aerosol, cloud and surface.
- Reflection and transmission of the atmosphere-surface system can be calculated from a radiative transfer model (RTM) when information to fully characterize the atmosphere and the surface is available.



Error Budget

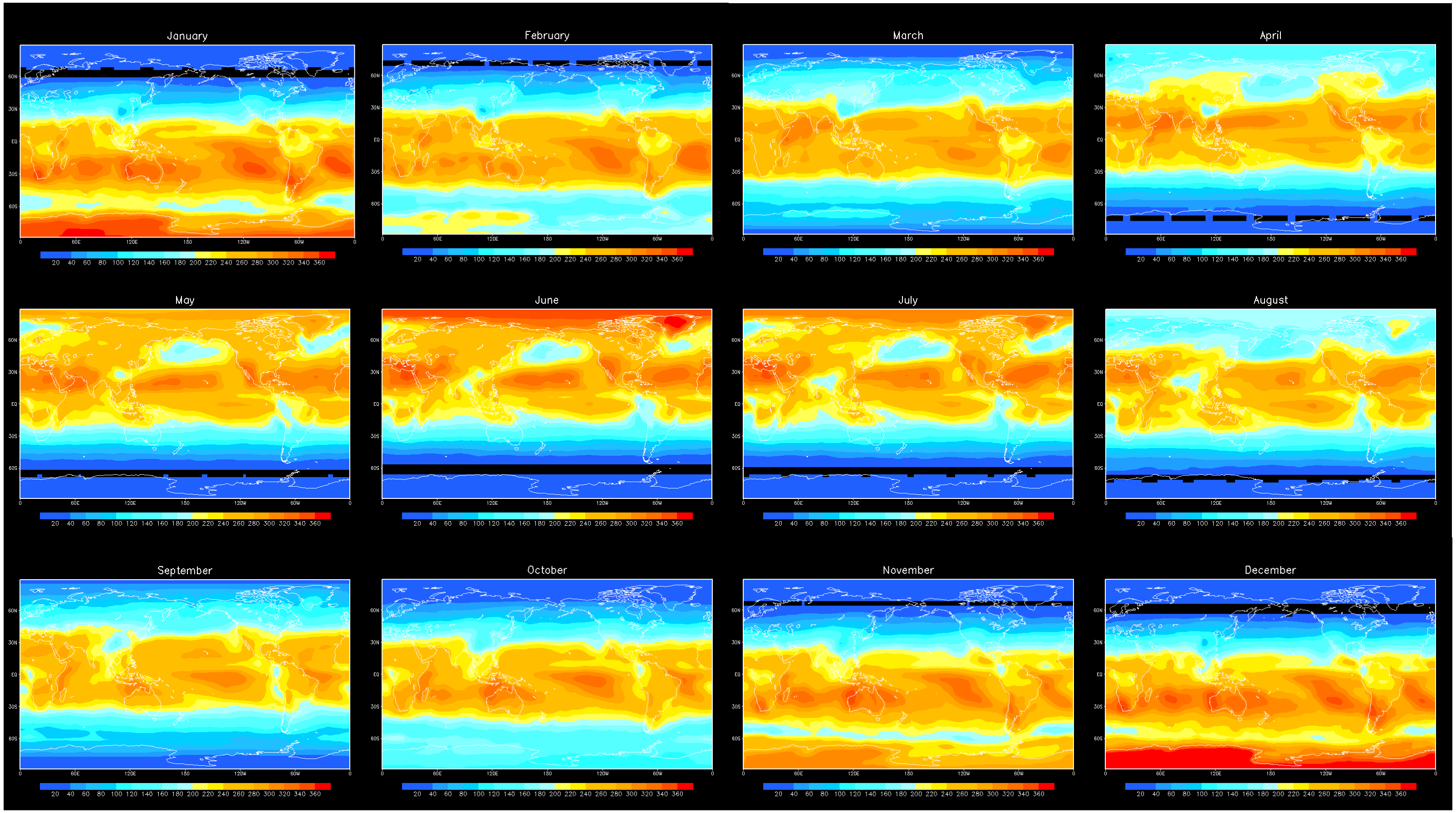
- Response to uncertainties in input parameters:
  - » 9% and 8% in precipitable water and ozone amount
  - » 30% in aerosol climatology optical depth
  - » 11% in cloud mask, and
  - » 4 µm in cloud effective radius.
- Evaluated difference between fluxes from perturbed and unperturbed inputs
- Less than 5 Wm^{-2} (<1%) change, except for cloud fraction (~25 Wm^{-2})



Long-term Satellite Solar Products at NESDIS

- **Historic, global, low-resolution, long-term product**
  - **SASRAB-V product:**
    - from International Satellite Cloud Climatology Product (ISCCP) radiance and ancillary data
    - with the **S**atellite **A**lgorithm for **S**hortwave **RA**diation **B**udget
    - global (geo+polar) at 280 km every three hours (nominal)
    - long-term (July 1983 onward)

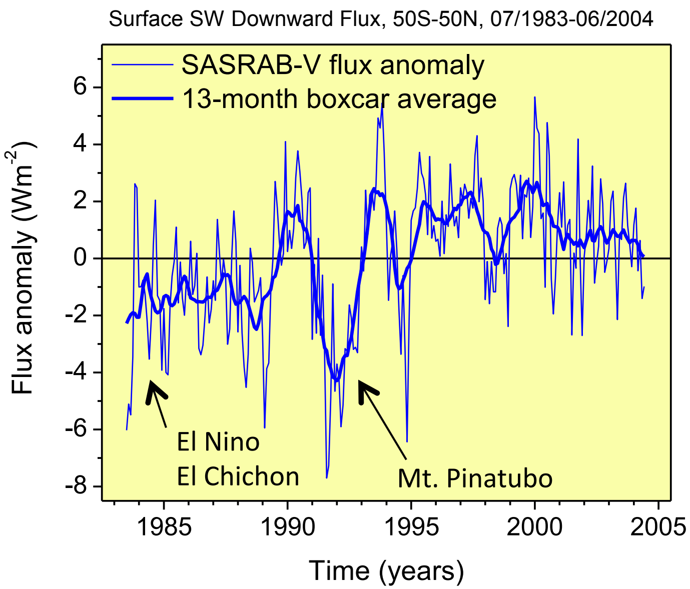
SASRAB 21-Year Average Insolation



Surface solar irradiance (Wm^{-2}) derived from the ISCCP D1 data using the SASRAB-V algorithm are averaged for each month for the years of 1984-2004.

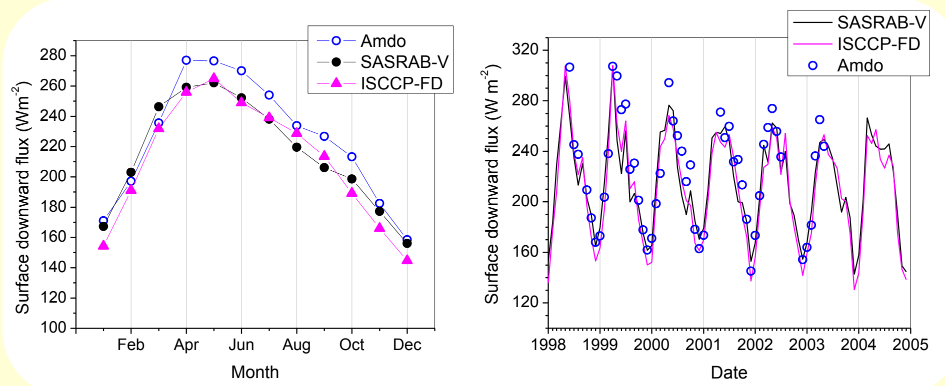
Variability of Insolation

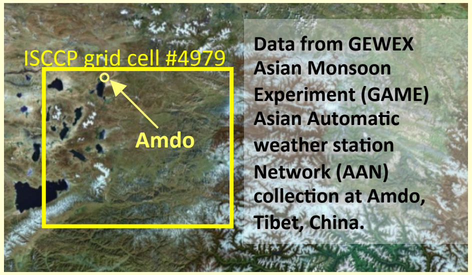
Global scale



- SASRAB-V data permits analysis of long-term variability of surface solar irradiance on global and regional scales:
  - global (50S-50N) insolation increased until ~2000; decreased after that

Grid scale



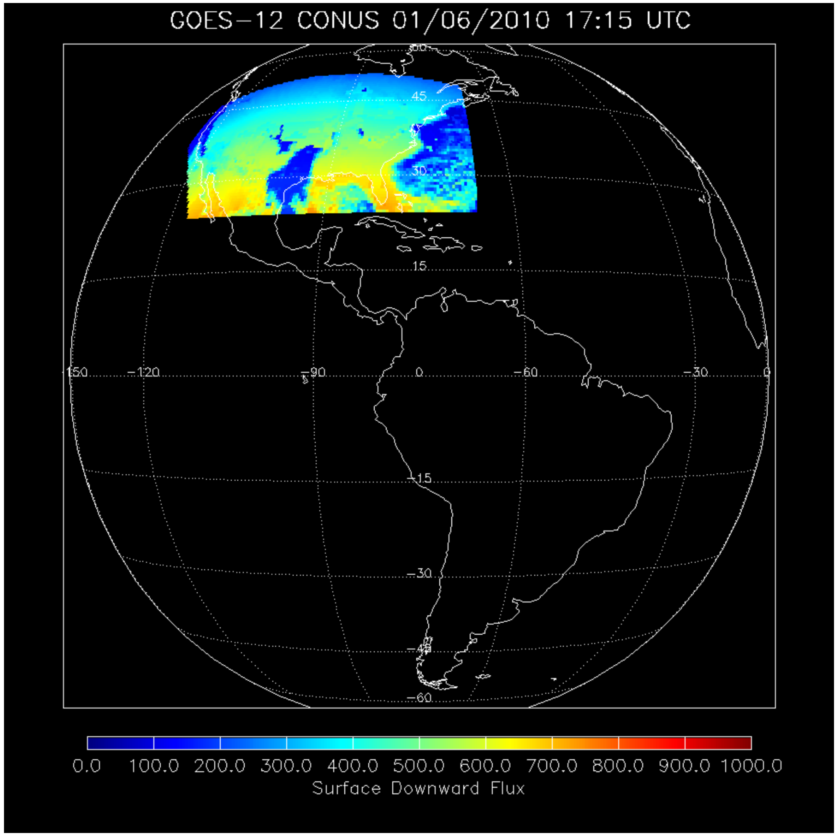


Data	Mean	SD	Min	Max
Amdo	224	43	145	307
SASRAB-V	215	37	153	307
ISCCP-FD	211	41	137	308

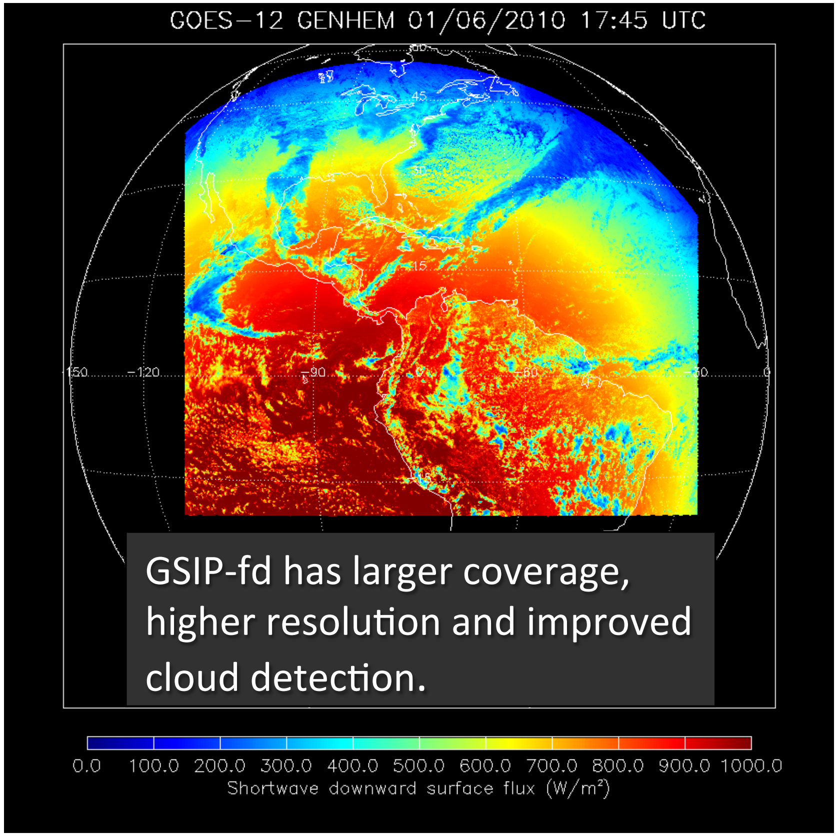
Time series of satellite and ground fluxes at Amdo, Tibet, China. The grid-cell averages of satellite estimates are similar and smaller than the ground average.

GSIP-fd Product Example

GSIP-CONUS

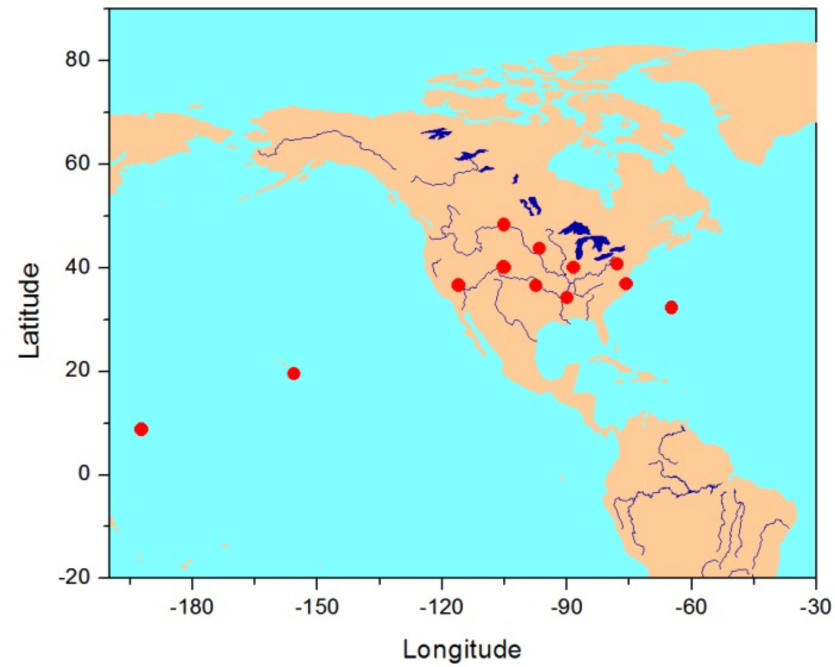


GSIP-fd



ABI DSR - MODIS data "sites"

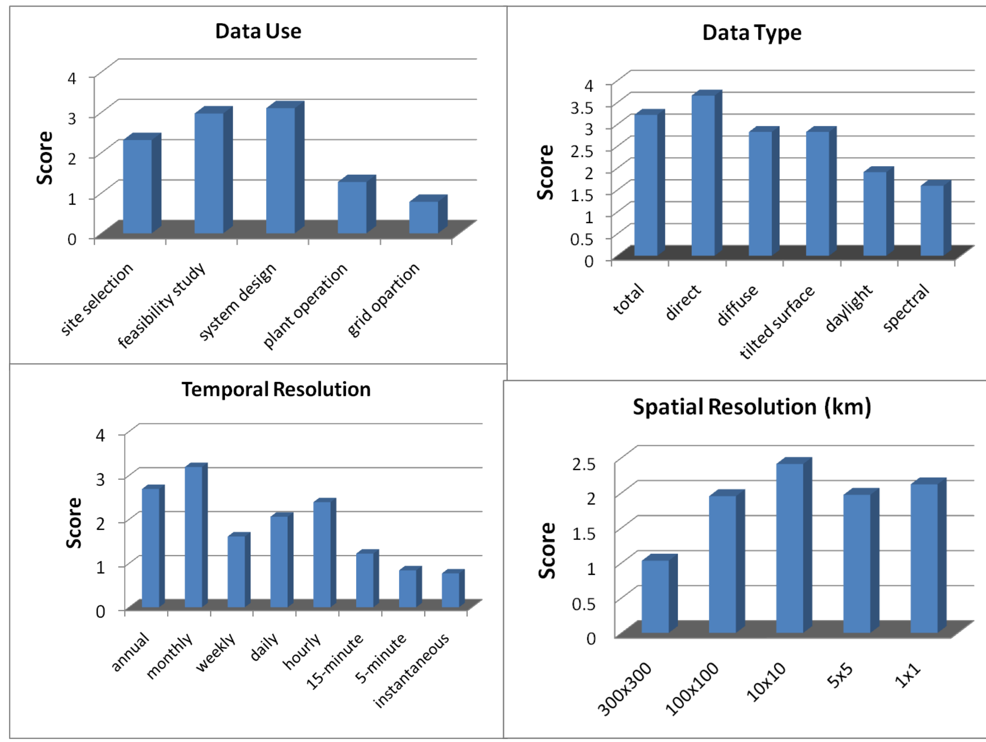
- Proxy MODIS data over 13 ground stations:
  - seven SURFRAD sites (BON, DRA, FPK, GWN, PSU, SXF, TBL);
  - CERES Ocean Validation Experiment (COVE) site,
  - Atmospheric Radiation Measurement Project (ARM) site (E13)
  - four Global Monitoring Division (GMD) sites (BER, BOU, KWA, MLO).



IEA User Survey Results

User survey of the Solar Heating and Cooling Program of the International Energy Agency (IEA) on Solar Resource Management (2007) (http://www.earthobservations.org/documents/sbas/en/54_International%20Energy%20Agency.pdf)

- Solar radiation data are most used for system design-site selection
- Most needed are monthly, annual and hourly direct and total radiation at 10x10, and 1x1 km resolution
- **No information on accuracy and precision required for SE applications**



Selected Solar Energy Specific Products

Average insolation (Amount of solar radiation incident on the surface of the Earth)
Midday insolation (Average insolation available within 1.5 hours of Local Solar Noon)
Clear sky insolation (Average insolation during clear sky days)
Clear sky days (Number of clear sky days (cloud amount < 10%))
Diffuse radiation on horizontal surface (Amount of solar radiation incident on the surface of the earth under all-sky conditions with direct radiation from the Sun's beam blocked)
Direct normal radiation (Amount of solar radiation at the Earth's surface on a flat surface perpendicular to the Sun's beam with surrounding sky radiation blocked)
Insolation at hourly intervals (Amount of solar radiation incident on the surface of the Earth during one hour)
Insolation clearness index (Fraction of insolation at the top of the atmosphere which reaches the surface of the Earth)
Insolation normalized clearness index (Zenith angle-independent expression of the insolation clearness index)
Clear sky insolation clearness index (Fraction of insolation at the top of the atmosphere which reaches the surface of the earth during clear sky days)
Minimum available insolation as % of average values over consecutive-day period (Insolation based on minimum consecutive-day insolation over various numbers of days within the month)